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Design Method for Nonimaging Solar Photovoltaic Concentrators Using Genetic Algorithms

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Abstract. Off-grid solar chargers are one of the ways forward to achieve universal access to affordable, reliable, sustainable and modern electricity. To achieve this goal, the sustainability aspect of the solar chargers must be further improved. Nonimaging, static solar photovoltaic (PV) concentrators reduce the amount of PV material and thus the embodied energy and greenhouse gas emissions of the solar PV panel, improve its recyclability and reduce the use of hazardous chemicals during its manufacturing, recycling and disposal stages. A novel nonimaging solar PV concentrator named circular rotational square hyperboloid (CRSH) was recently proposed for portable solar systems for developing countries. To further reduce the material usage and production time of the concentrator while achieving an optical concentration ratio above 3x within the angles of incidence of $\pm 40^\circ$, the parameters of the design were optimised using genetic algorithms. The optimisation parameters are discussed and the influence of the objective function on the optimised design is presented. The genetically optimised circular rotational square hyperboloid (GOCRSH) concentrator shows an improved gain-to-volume ratio compared to the CRSH and to several nonimaging solar photovoltaic concentrators proposed for building integrated concentrated PV.

INTRODUCTION

Universal access to affordable, reliable, sustainable and modern energy by 2030 is one of the UN Sustainable Development Goals [1]. Yet, worldwide, over 1.1 billion people lack access to electricity. Due to 80% of the affected people living in rural areas in developing countries and having limited financial means [2], small portable solar chargers are one of the main technologies to help achieve this goal [3]. Silicon photovoltaic (PV) modules are mainly used for portable solar chargers. While these have a smaller environmental impact than their competitors from thin-film technologies, the production of silicon is very energy intensive leading to increased greenhouse gas (GHG) emissions and involves the use of toxic substances which can harm workers and the environment [4]–[6]. Considering the number of solar chargers needed to achieve universal access to clean affordable power, the sustainability aspect of the solar chargers must be further improved.

Solar PV concentrators have the potential to reduce the amount of energy required for manufacturing of solar PV modules, improve their recyclability and reduce the use of hazardous chemicals during their manufacturing, recycling and disposal [7]. For usability, a solar concentrator needs to have a sufficiently large acceptance angle (defined at 90% of the maximum power) to enable full battery charge without tracking, have low operation and maintenance costs and have a small volume to maintain portability. A novel nonimaging concentrator design was recently proposed for portable solar systems for developing countries [8] and is here referred to as circular rotational square hyperboloid (CRSH).

The CRSH has a rotationally symmetric entrance aperture, a hyperbolic side-profile and a 100 mm² square exit aperture (Fig. 1). The entrance aperture has been designed point by point according to the SIngLe Optical surface design method [9], [10]. This design method guarantees that all rays within the acceptance angle reach the exit aperture, the typical geometrical concentration ratio (ratio of the entrance aperture area to the exit aperture area)

however, is around 2x. To increase the concentration ratio to 3x and higher, the exit aperture width was reduced. This led to a reduction in optical efficiency¹ in particular at angles of incidence close to the acceptance angle. To increase the optical efficiency at larger angles of incidence, a hyperbolic side profile was employed [8]. Since the exit aperture width and the side profile have been changed from the original design method, it is to be investigated if a different curvature and diameter of the entrance aperture and therefore a different curvature of the hyperbolic side profile would yield better results. This paper proposes to optimise the surface parameters using genetic algorithms (GAs). The goal of the optimisation is to achieve a more compact design and an optical concentration ratio² (C_{opt}) within the angles of incidence of $\pm 40^\circ$ above 3x to enable over five hours of electricity generation at 3x concentration.

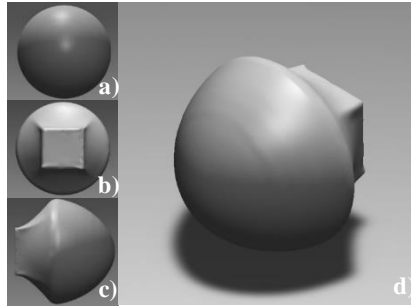


FIGURE 1. CRSH design: a) circular entrance aperture, b) square exit aperture, c) hyperbolic side-profile, d) isometric view

CONCENTRATOR OPTIMISATION

Since the CRSH design is not etendue preserving, its optical efficiency at various angles of incidence and therefore its average C_{opt} needs to be determined through 3D raytracing. The MATLAB integrated raytracing program *Optometrika*³ was used in this work. *Optometrika*'s library is written in MATLAB classes and is fully vectorised enabling fast raytracing. The surfaces of the CRSH were integrated into *Optometrika*'s library using a lens class for user defined surfaces called "GeneralLens", which requires parametric representation of the surface coordinates and normals.

Since rotationally symmetric concentrators designed in 2D are not etendue preserving and therefore not ideal, the research into global optimisation of nonimaging concentrators was introduced by Shatz and Bortz [11] in 1995. They were the first to publish an optimisation procedure of the rotational compound parabolic concentrator (CPC) and concluded that nonimaging optical design problems are multimodal, meaning that multiple local optima exist for a set of objectives and constraints. Hence, global optimisation techniques are best suited for finding the optimal (or near optimal) parameters of the CRSH. Global optimisation algorithms can be categorised into deterministic and probabilistic algorithms. Deterministic optimisation algorithms are used when the relation between the parameters and the desired solution is known. Probabilistic optimisation is used when the relation between the input parameters and the desired solution is not clear or too complex, or when the search space is too large to be explored deterministically. In contrast to deterministic methods, worse solutions get accepted, as it increases the search space and prevents mistaking the local optimum for the global optimum [12], [13].

Introduction to Genetic Algorithms

Probabilistic optimisation was chosen for the problem at hand since it does not require the knowledge of a suitable starting model. Genetic algorithms (GA), which are part of evolutionary algorithms, are suitable for finding the global optimum in complex search spaces riddled with many local optima [14]. GAs are based on the Darwinian notion of "survival of the fittest" where the fitter individuals have a higher chance to be selected for mating and to pass on their genes onto future generations. The individuals within a population are evaluated simultaneously. An individual is characterised by its genes which form the chromosomes of an individual. The individuals in this case are concentrator designs which have different parameters (chromosomes). Like in procreation, parts of the

¹ Ratio of the radiant flux at the exit aperture to the radiant flux at the entrance aperture.

² Product of the optical efficiency and the geometrical concentration ratio.

³ The software is available for download under <https://uk.mathworks.com/matlabcentral/fileexchange/45355-optometrika>.

chromosomes of the selected pair are swapped to create new individuals. This process is called crossover. A further operator called mutation changes single genes in the chromosomes of individuals. While through crossover the algorithm converges to the best solution using the genetic material present in the population, mutation increases the search space by introducing new genes [14]. The properties of the individuals evolve over generations directed by selection, crossover and mutation to produce fitter and fitter individuals (Fig. 2) [15].

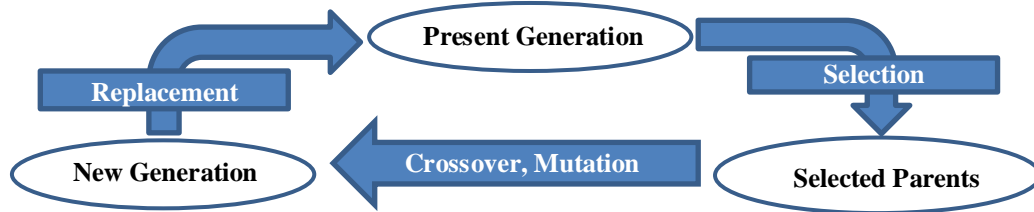


FIGURE 2. Basic evolution cycle adapted from [22]

GA Parameters

The population size N was set to 50 individuals. The first generation starts with random parameters which are spread throughout the search space. The search space can be limited by boundaries if these are known or can be completely unrestricted. The parameters are encoded in binary using the MATLAB integrated function *dec2bin*. The performance of the individuals is evaluated based on an objective function. This function defines how close the guesses / individuals are to the desired solution or how they compare to other guesses / individuals. The aim is to maximise the average C_{opt} within the angles of incidence of $\pm 40^\circ$ and to achieve a minimum concentrator volume V (Equation 1). The two optimisation aims are combined into one objective function (Equation 1) and each individual is allocated a fitness value f_i . For the objective function, the sum of the C_{opt} at every angle of incidence between 0° and 40° was used. The selection probability f_s of each individual is calculated by dividing its fitness value by the sum of all fitness values within the population (Equation 2).

$$f_i = \frac{\sum_{0^\circ}^{40^\circ} C_{opt,i}}{\sqrt[3]{V_i}} \quad (1)$$

$$f_{s,i} = \frac{f_i}{\sum_1^N f_i} \quad (2)$$

There are different approaches to select individuals for the next generation. Rank, tournament and fitness proportional selection are the most common selection methods [16]. Tournament selection and fitness proportional roulette wheel selection with fitness scaling were compared for the problem in place and tournament selection was found to achieve better results. In tournament selection, individuals are selected based on their relative rank rather than on their absolute rank or proportional to their fitness [17]. From a number of randomly selected individuals, called *tournament size*, the fittest individual is chosen for mating. The tournament size is typically between 2 and 3 individuals; the larger the tournament size, the lower the chance for the less fit individuals to go forward [16], [17]. The tournament size was set to 2 and selection was repeated until 50 individuals were selected.

In crossover, parts of the chromosomes are swapped between two selected individuals. The chromosomes are divided into two parts for 1-point crossover or into three parts for 2-point crossover. For a 2-point crossover the middle part is swapped between the two individuals (Table 1). Multiple point crossover and crossover at every gene are also possible, yet, the later can be very disruptive to the genetic material. Crossover is performed according to a user-defined probability P_c , which is typically between 0.4 and 0.9 [14], [16]; with $P_c = 0.5$, half of the individuals undergo crossover. A random number R_c is generated; if $R_c < P_c$, crossover is performed, else the selected pair goes into the next generation unchanged. 2-point crossover with a probability of $P_c = 0.7$ was applied to this optimisation.

TABLE 1. Example of a 2-point crossover

Chosen parameters		2-point crossover	Changed parameters	
36 23 15	100 100 010111 001 111		100 011 111111 011 111	35 63 31
19 63 28	010 011 111111 011 100		010 100 010111 001 100	20 23 12

Mutation prevents the population from converging too quickly, by introducing random changes into the genetic material (Table 2) [18], [19]. The mutation operator swaps a binary digit of a parameter according to the user defined mutation probability P_m [14]. Having tested P_m values between 0.1 and 0.01, P_m was set to 0.01. The algorithm steps through each gene of the chromosome and generates a random number R_m between 0 and 1. If $R_m < P_m$, the bit is flipped, else it remains unchanged. After crossover and mutation, the new generation is set. However, crossover and mutation might produce unfeasible parameters. It is therefore checked if all parameters are within the specified boundaries.

TABLE 2. Example of mutation

Initial parameters	Changed parameters
01011101000	01011100000
01011110101	01111110101

Optimisation Results

The conversion speed of the algorithm was identified for the chosen parameters and the stopping criteria was set accordingly to 70 generations. Running the optimisation algorithm with the parameters discussed in the previous section, the genetically optimised circular rotational square hyperboloid (GOCRSH) has a volume of 2700 mm³, a maximum height h_m of 12.74 mm and an average $C_{opt\pm 40^\circ}$ of 2.94x. The height of the concentrator is important for the injection moulding manufacturing process to reduce the mould cooling time. To further decrease the volume and the height of the concentrator, h_m is included into the objective function (Equation 3).

$$f_i = \frac{\sum_{0^\circ}^{40^\circ} C_{opt,i} - h_{m,i}}{\sqrt[3]{V_i}} \quad (3)$$

With the new objective function, the optimised concentrator design has a volume of 2271 mm³ a maximum height h_m of 11.74 mm and an average $C_{opt\pm 40^\circ}$ of 2.77x. Various objective functions have been tested for the problem in place. To allow for concentrator designs with different volumes and gains, the optimisation is performed with different objective functions by changing the root k (Equation 4) to $k = [2; 3; 3.6; 4]$. The influence of the objective function on the properties of the GOCRSH is shown in Fig. 3.

$$f_i = \frac{\sum_{0^\circ}^{40^\circ} C_{opt,i} - h_{m,i}}{\sqrt[k]{V_i}} \quad (4)$$

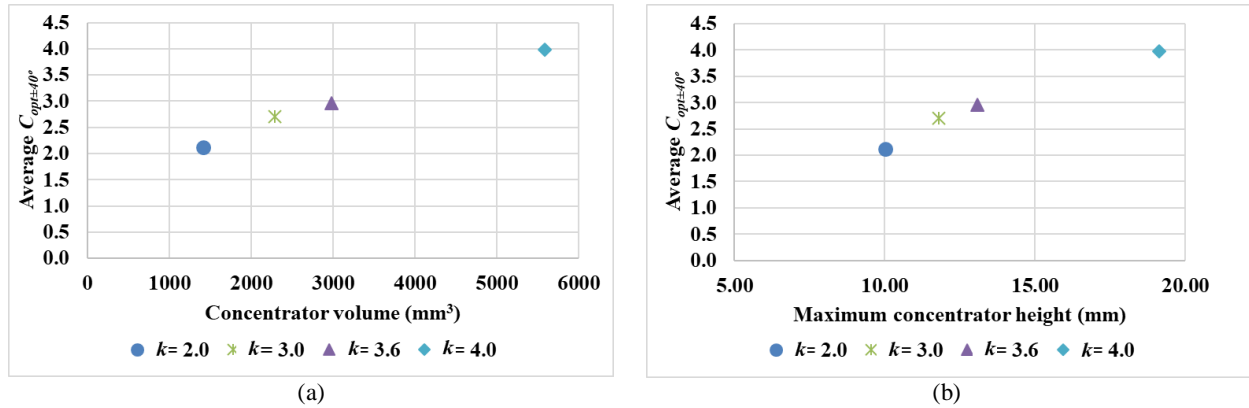


FIGURE 3 Influence of the objective function on the average $C_{opt\pm 40^\circ}$ and (a) concentrator volume (b) concentrator height

Increasing k from 2 to 4, the influence of volume on the fitness of the individual becomes less significant resulting in an optimised design with a volume greater 5000 mm³ but also a higher gain. The geometrical concentration ratios of the GOCRSH concentrators achieved through the optimisation with the k -values of 2, 3, 3.6, and 4 were 2.12x, 3.34x, 3.96x and 4.90x respectively. The optimisation for the objective function with $k = 3.6$ was repeated with a higher mutation rate of $P_m = 0.1$ and the stopping criteria was set to 200 generations. The resulting characteristics of the GOCRSH were similar: a volume of 3064 mm³, a maximum height h_m of 13.16 mm and an average $C_{opt\pm 40^\circ}$ of 3.03x.

The gain-to-volume ratio of the GOCRSH is compared to the CRSH (A,B,C) [8] and to several nonimaging concentrators proposed for building integrated concentrated photovoltaics (BICPV) in Table 3 and Fig. 4. It can be observed from Fig. 4 that the GOCRSH have a better gain-to-volume ratio than the not optimised CRSH and several BICPV concentrators (RACPC [20], RADTIRC [21], 3D CCPC [22], SEH [22], Aspheric lens [23]). The average η_{opt} within the angles of incidence of $\pm 40^\circ$ ($\eta_{opt\pm 40^\circ}$) is also shown in Table 3. There is no tendency however to η_{opt} increase or decrease through the use of optimisation, since η_{opt} was not included in the objective function.

TABLE 3. Comparison of the GOCRSH with the CRSH and several BICPV concentrators for a 100 mm² square solar cell

Design	CRSH			GOCRSH				Several concentrator design for BICPV				
	A	B	C	$k = 2$	$k = 3$	$k = 3.6$	$k = 4$	RACPC	RADTIRC	3D CCPC	SEH	Aspheric lens
Volume in mm ³	7570	4272	4045	1397	2271	2961	5594	8538	8230	3968	4019	1600
Av. $C_{opt\pm 40^\circ}$	3.23	3.27	3.08	2.11	2.73	2.99	3.97	3.41	3.90	2.64	1.80	1.88
Av. $\eta_{opt\pm 40^\circ}$ in %	80.55	90.83	89.02	99.32	81.74	75.34	80.87	92.92	79.43	73.13	45.00	47.00

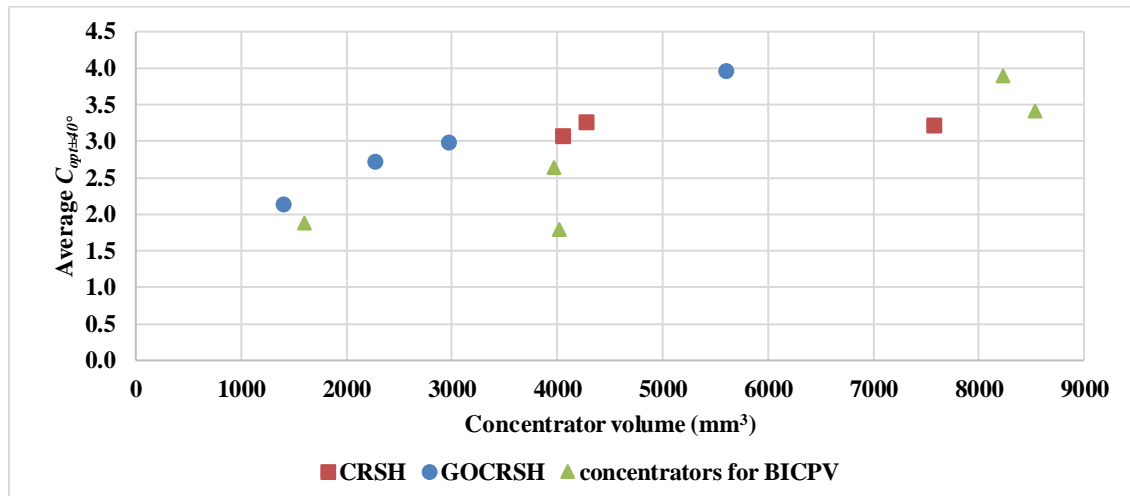


FIGURE 4. Comparison of the GOCRSH with the CRSH and several BICPV for a 100 mm² square solar cell

CONCLUSION

To achieve the goal of universal access to affordable reliable, sustainable and modern electricity, the sustainability aspect of solar chargers needs further improvement. Nonimaging, static solar PV concentrators reduce the amount of PV material and can therefore reduce the embodied energy and GHG emissions of the solar PV module, improve its recyclability and reduce the use of hazardous chemicals during its manufacturing, recycling and disposal. A novel nonimaging solar PV concentrator named circular rotational square hyperboloid (CRSH) was previously proposed for portable solar systems for developing countries. To minimise the material usage and production time of the concentrator while maintaining an optical concentration ratio above 3x within the angles of incidence of $\pm 40^\circ$, the parameters were optimised in this paper using GAs. The proposed optimisation algorithms were discussed and the influence of the objective function on the optimised design was presented. The genetically optimised circular rotational square hyperboloid (GOCRSH) concentrator showed an improved gain-to-volume ratio compared to the CRSH and compared to several BICPV concentrators. It has therefore been shown that a more compact and less material intensive design can be achieved through the optimisation of the parameterised CRSH design by GAs.

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